Combined Observational Methods for Positional Awareness in the Solar System (COMPASS): Expanding the Space Service Volume Throughout Cislunar Space

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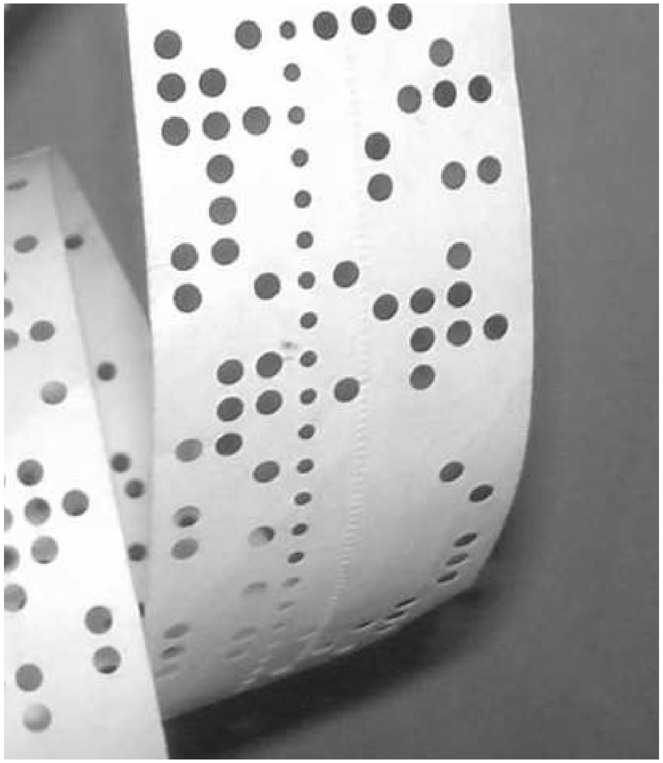
It all Started with Punched Paper Tape



VLBI to the Lunar ALSEPS

- In the mid-1970's I worked with Bob King at MIT.
- His office had a section filled with punched paper tape.
- That was the ALSEP VLBI phase data [King et al., 1976].
  - Later on, the paper tape started cracking, which was a problem.
- A very narrow bandwidth (kHz) S-band transmitter was used to determine relative positions of the ALSEPS on the Moon to "about 30 m along the earth-moon direction and about 10 m in each of the two transverse coordinates."
- No quasars were involved in this VLBI!
- Now, we are going back to the Moon. How can VLBI help with this effort?

Extending the Space Service Volume (SSV) to CisLunar Space

NASA, the Air Force and Industry are planning for a vast increase in operations in Cislunar Space

- In LEO there are plans for large constellations (swarms) of spacecraft, up to thousands of separate spacecraft.
  - The DARPA / Air Force “Blackjack” program, for example, is predicated on this.
- As these technologies mature, these large scale deployments will be inevitably extended into Deep Space.
- In August, 2018, Goddard’s Planetary Cubesat Science Institute (PCSI) hosted the Second Planetary CubeSats Symposium.
- At this meeting, there were predictions of the deployment of 1000’s of Smallsats in cislunar space in the relatively near future.
  - There is no plan yet to navigate / position such large spacecraft swarms at that distance. Existing systems either won’t reach or won’t scale large numbers of small spacecraft.
- COMPASS UWB can be incorporated into local positioning networks, providing a unified solution for this and the PNT problem in lunar operations.

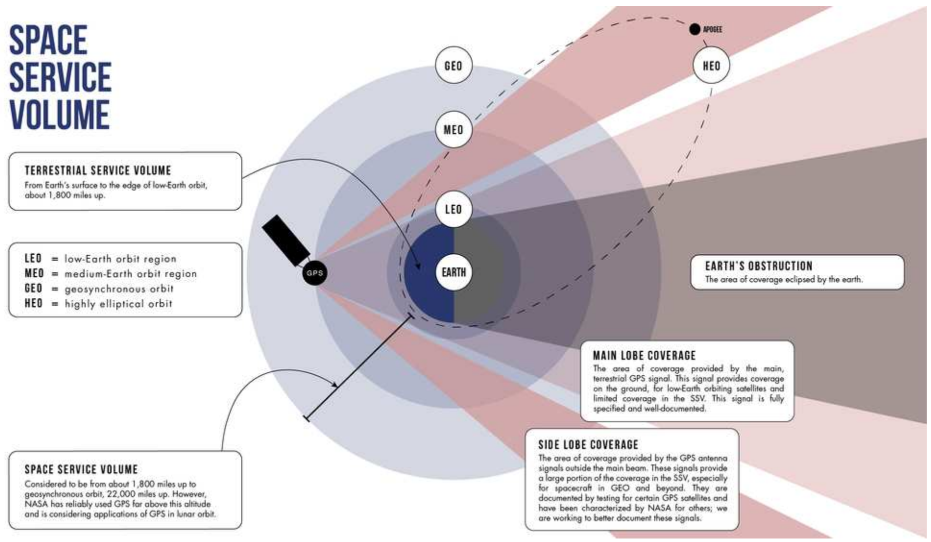
DARPA Blackjack plans for LEO. Will the Moon look like this in 2030?

Image from DARPA.

An Extended Space Service Volume Will Enable Advanced Applications

- Satellite Servicing
  - Involves Rendezvous, possibly with crippled satellites.
  - As a rule of thumb, the relative position should be known to within 10% of the inter-vehicle range.
- Satellite Formation Flying
  - Will enable a wide variety of new classes of missions.
  - Requirements can be as low as 1 meter absolute positioning and cm-level relative navigation.
- Lunar Orbital / Surface Operations
  - The Gateway will require accurate backup navigation, and will likely host many free-flying Small-Sat / CubeSat missions. These will all need positional awareness.
  - Lunar surface operations (rovers, hoppers, construction) will have very similar requirements to Formation Flying.
  - Again, requirements can be as low as 1 meter absolute positioning and cm-level relative navigation.
  - Operations on the Far Side or in Permanently Shadowed Regions will require PNT extension.
- Planetary Defense.
  - There is interest in the Planetary Defense Office in "tagging" Potentially Hazardous Objects (PHO) with beacons or transponders.
  - This will fit naturally into COMPASS operations, although PD will set stringent limits on beacon longevity, and will require more power than CisLunar beacons.

GPS and the Space Service Volume in Cislunar Space.



From NASA/SCaN.

GPS Sidelobes can be observed out to CisLunar Space, but the Geometric Dilution of Precision will be Severe.

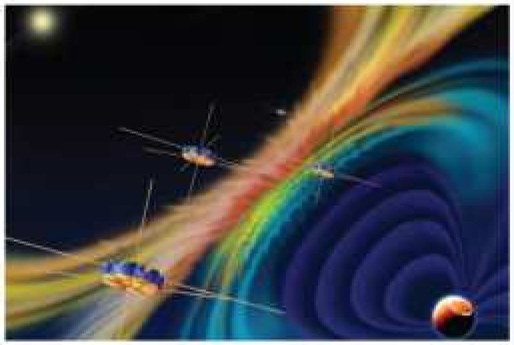
Recent SSV Experiences: NASA MMS Mission

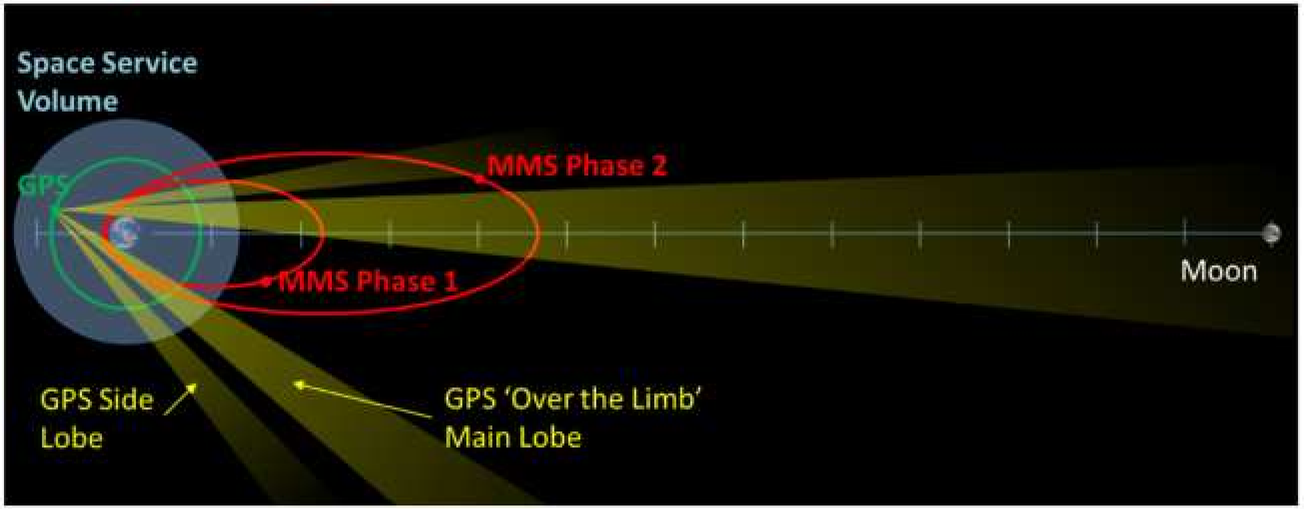
Magnetospheric Multi-Scale (MMS)

- Launched March 12, 2015
- Four spacecraft form a tetrahedron near apogee for performing magnetospheric science measurements (space weather)
- Four spacecraft in highly eccentric orbits
  - Phase 1: 1.2 x 12 Earth Radii (Re) Orbit (7,600 km x 76,000 km)
  - Phase 2B: Extends apogee to 25 Re (~150,000 km) **(40% of way to Moon)**

MMS Navigator System

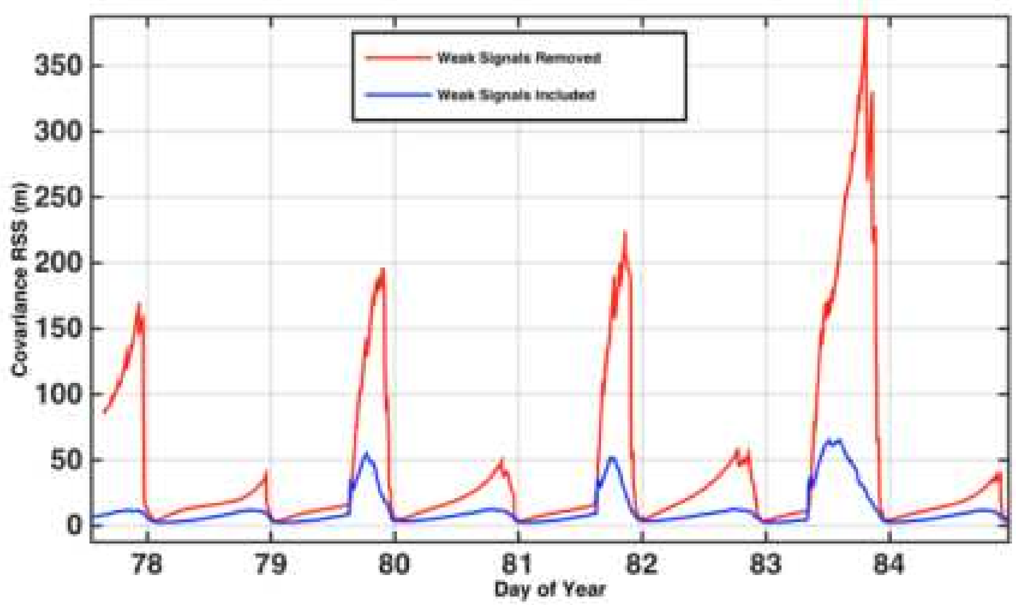
- GPS enables onboard (autonomous) navigation and near autonomous station-keeping
- MMS Navigator system exceeds all expectations
- At the highest point of the MMS orbit Navigator set Guinness world record for the highest reception of signals and onboard navigation solutions by an operational GPS receiver in space
- At the lowest point of the MMS orbit Navigator set Guinness world for fastest operational GPS receiver in space, at velocities over 35,000 km/h





(Courtesy Benjamin Ashman, GSFC.)

MMS SSV Lessons Learned.



MMS response to apogee maneuvers with side-lobe signals (blue) and without (red)

Over the Shoulder GNSS can approach Dekameter accuracy at CisLunar distances using sidelobe signals, which substantially improve GNSS availability and GDOP in CisLunar Space. (Courtesy Benjamin Ashman, GSFC.)

COMPASS - a Component of an Extended Space Service Volume

- A CisLunar SSV will clearly involve use of the GPS
  - This will be “over-the-shoulder,” and will be limited by the Geometrical Dilution of Precision (GDOP) this causes.
  - A single point GPS extension, say at the Gateway or at a Lagrange point, will help availability but will not solve the GDOP problem.
- For Lunar Surface Operations, laser retroreflectors will provide highly accurate ranging, but limited positioning.
- And, of course, there are existing NASA Spacecraft Tracking assets for high value and crewed missions.
  - These are not set up to handle hundreds or thousands of spacecraft.
- There is, however, another **existing** International infrastructure that can observe spacecraft in CisLunar Space - the VLBI Global Observing System (VGOS).
  - VGOS was developed with the strong participation and support of the Goddard VLBI Group.
  - The existing and planned VGOS network **can** track 1000’s of spacecraft in CisLunar space (and beyond), **if** these spacecraft carry suitable VLBI beacons.
  - This has been done using legacy VLBI with, e.g., Huygens in the Titan atmosphere. The TRL is high.
- COMPASS (Combined Observational Methods for Positional Awareness in the Solar System) is our proposal to use this technology for routine positional awareness in CisLunar space and beyond.
  - COMPASS will be a positioning system suitable for SSV use, based on Ultra-Wide-Band (UWB) Beacons for Positioning, Navigation and Timing (PNT) in Cislunar space.

Positional Awareness in the 1000 Spacecraft Regime

- All of the problems of constellation management in Earth orbit are multiplied in deep space.
- Principles that I think are useful to follow include
  - The goal should be a GPS level of service, something that is just there and just works.
  - Technology should be Commercial Off The Shelf (COTS) as much as possible. In Cislunar space and below, GPS is likely to be an important part of this.
  - There should be a unified set of solutions. Smallsat developers should **not** have to develop navigation solutions from scratch.
  - Swarms and surface operations will need accurate relative positioning over (fairly) short ranges. If possible, that should be done with the same technology as for navigation, but at least they should mesh together smoothly.
  - RFI is a potentially serious problem, and ultra wide-band solutions must be considered.
  - Navigation support is not enough. Collision avoidance requirements means that positional awareness will be needed back on Earth as well.
  - In the (relatively) far future, inverse optical VLBI from Earth or LEO may provide very accurate truly autonomous Cislunar navigation. But for now, the focus is on RF methods, although retroreflectors will be an important adjunct for surface science.
  - In addition Planetary Protection has expressed the desire to "tag" Potentially Hazardous Objects (PHOs) (asteroids or comets). COMPASS should support monitoring of PHO positions "out of the box."

Tracking Lunar Spacecraft with Very Long Baseline Interferometery (VLBI)

Why VLBI?

- VLBI offers a number of attractive features for a cislunar positional awareness system.
  - Centimetric VLBI can provide sub-nanoradian angular accuracy, corresponding to $<$ 40 cm transverse positional accuracy at the lunar distance.
  - The parallax would provide $\sim$30 meter radial position estimates.
  - The angular noise floor, from ICRF work, is maybe a factor of 5 better, or 8 cm at the Moon.
  - An SEFD of 1000 JY or less would enable integration times of a few seconds even with transmitter power of a few milliwatts.
- COMPASS therefore proposes that VLBI be used for routine positioning of the coming flood of cislunar smallsats. .
- CisLunar COMPASS will need a chipsat sized "navigation patch" be developed to allow for simple smallsat navigation support.
- In parallel with this a registry should be established to give deep space small sats a unique identifier, which should be integrated into the navigation system and broadcast by each beacon.
  - This would function something like the MAC address in terrestrial wireless networks.

How Would COMPASS Work?
(and this is where we need advice and comments!)

- A UWB navigation beacon would be developed.
- There would be a Registry, which would assign a unique identifier (ID) to each spacecraft (or each navigation beacon).
  - I would suggest a 24 bit (16,777,216 numbers) address space for "future proofing."
  - Ideally, the ID would also map into a DTN ID and even maybe a IPv6 address suffix.
- The Navigation Beacon would broadcast a beacon signal (including its ID) on a regular basis.
  - The beacon code format will be chosen to interoperate with local communications and relative navigation.
  - The beacon would be ruggedized to potentially outlast the mission (especially for Lunar surface use).
  - Optical retroreflectors or blinking diodes could be included to meet some needs.
- The terrestrial VGOS network would observe the beacon catalog on a regular basis (daily or weekly).
- The goal would be to obtain a fix with $\lesssim$ 10 seconds of observing, and observe at least 10 (and ideally many more) beacons in one beam.
- 1000 spacecraft would thus require order 1000 seconds per day (mostly when the Moon was up).
  - This could be worked into many regular observing session, and would require payments.

VLBI Lunar Beacon SNRs

- The basic equation [Pogrebenko et al., 2004] is

$$SNR = t_{int} \frac{\eta \, \pi \, D^2}{4 \, kT_{sys}} \left(\frac{P \, G_{transmit}}{4 \, \pi \, f \, R^2} \right) \quad (1)$$

  where η is the net VLBI efficiency, k the Boltzmann constant, T_{sys} the system temperature, D the antenna diameter, R the distance to the source, and P the transmitter power. f is the UWB loss factor, about 11.3 for 802.15.4a.

- We assumed the availability of two VLBI antennas,and typical values for the 25 meter VLBA telescopes.
  - For the VLBA, T_{sys} = 26.6 K and η = 0.55

- The VLBA could in theory detect a 1 milliWatt UWB transmitter at the lunar distance with 1 second integrations and an SNR of 10.
  - This needs to be tested.

- As a broadband source, the navigation beacon would be a 0.4 milliJansky radio source.

OCEL: Observing the Chang'e 3 Lander with VLBI

- VLBI is again being done with a Lunar Lander - the Chinese Chang'e 3 [Klopotek et al., 2019].
  - These were scheduled in IERS / IVS RD VLBI sessions.
  - The Spacecraft broadcasts Differential-One-way-Ranging (DOR) tones centered at 8.470 GHz: $\pm$19.25 MHz & $\pm$3.85 MHz, plus a 50 MHz Communication channel at 8.496 GHz
- So far, only group delay has been used.
- Result sigmas are $\sim$ 4.5 meters in latitude and 8.9 meters in longitude.

OCEL Results

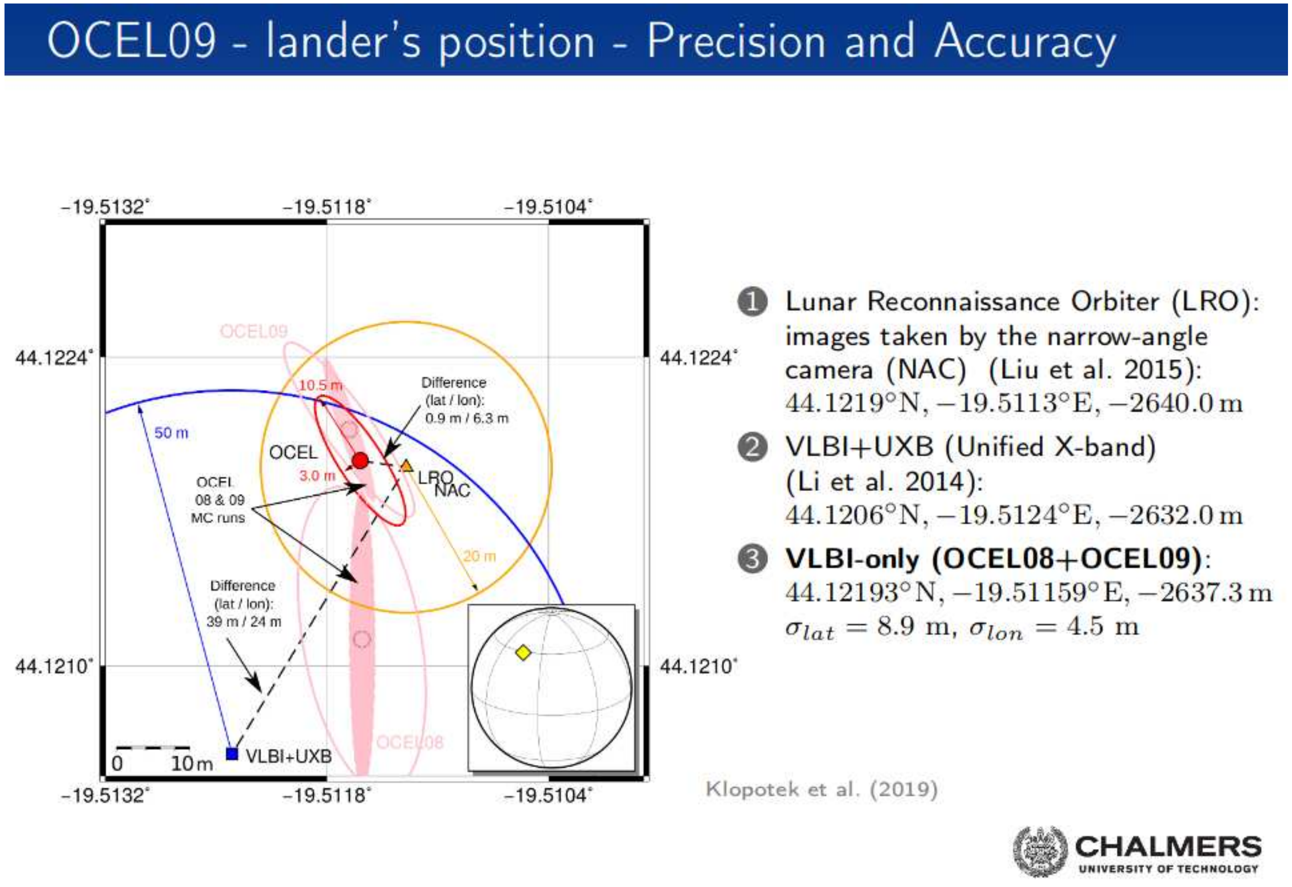
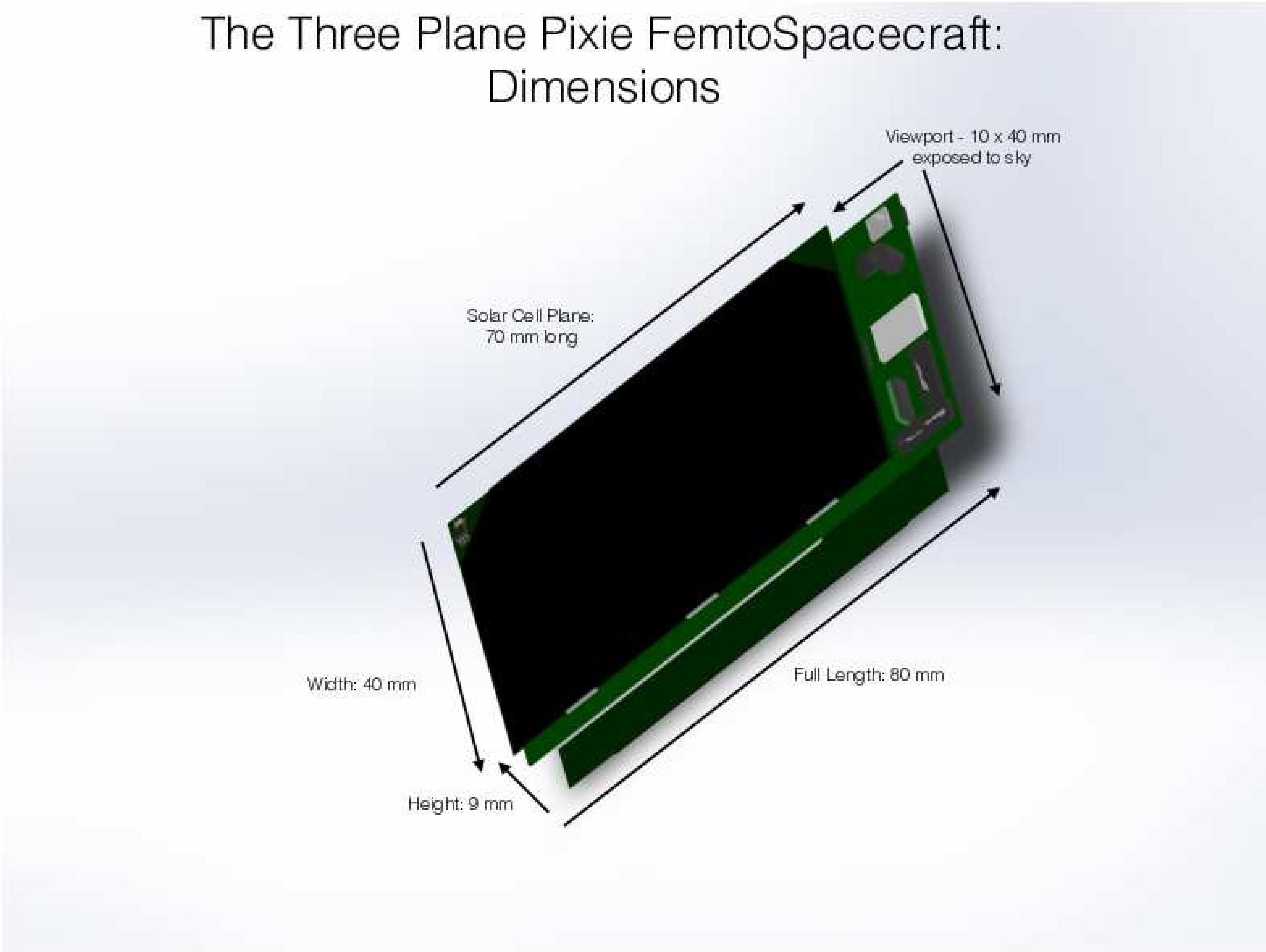


Image from Klopotek et al. [2019].

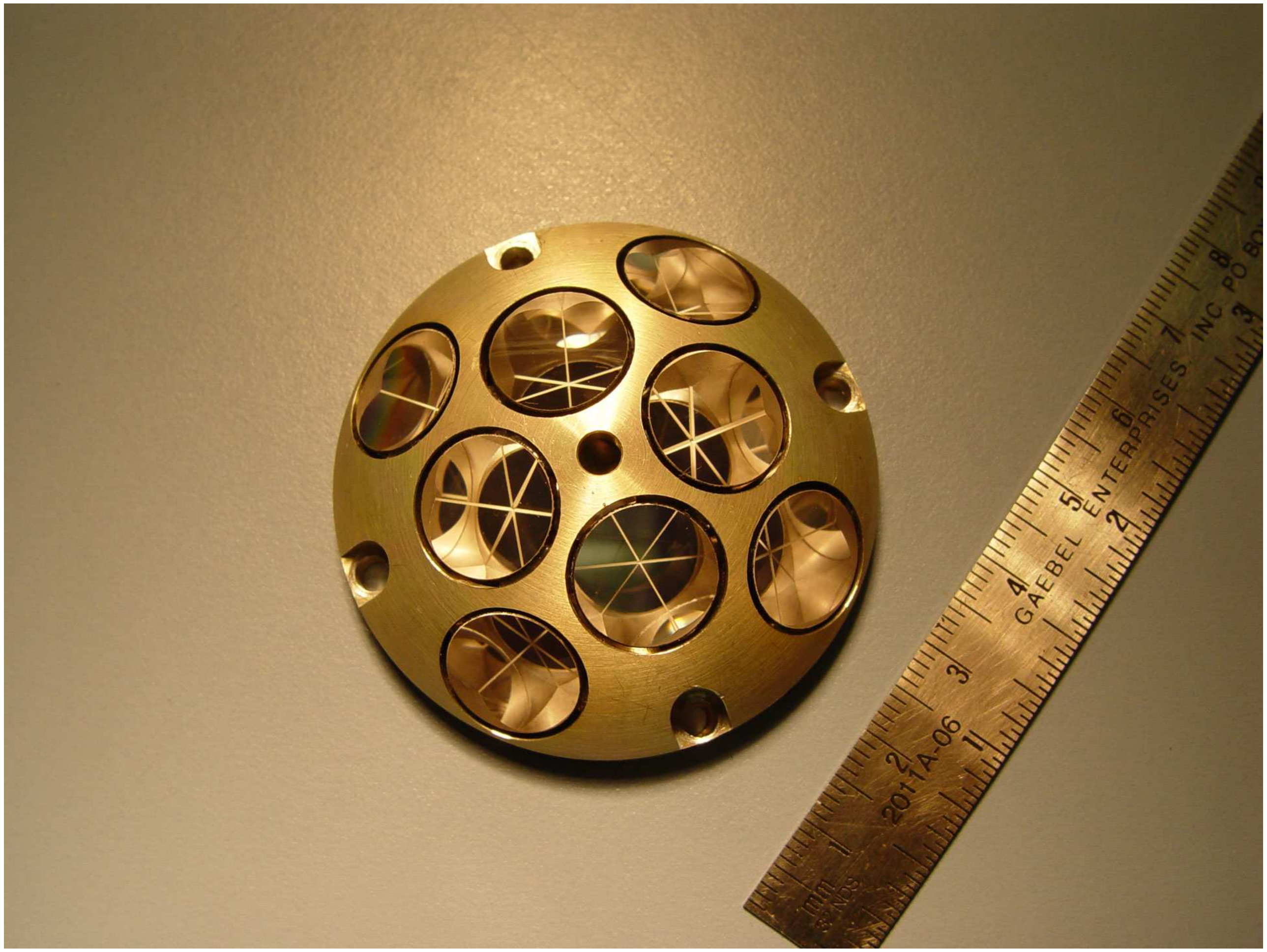
A Landed Surface Geodetic Station

The “Pixie” Beacon.



Combine our Pixie full sized beacon...

The “Beresheet” Retroreflector (made here at GSFC).



... with the Retroreflector sent to the Moon with Beresheet and (ideally) a suitable GPS receiver. //Result: A lunar geodetic station not much larger than a cell phone!

Conclusions

- The SmallSat revolution will require a new ways of doing work in space.
  - E.g., SmallSat swarms in Deep Space.
- Navigation beacons should become routine in Lunar exploration.
  - This engineering can and should be expanded to support missions to the Asteroids, Mars and even the Moons of Jupiter.
  - Small nuclear batteries should be seriously considered to power beacons in the lunar night, and for long term planetary defense beacons.
- In the context of space habitats or crewed bases on other worlds, this technology should integrate with both sensor nets and communication networks in the vicinity of the base / habitat.
- A very demanding customer will be the Gateway itself and SmallSats near the Gateway, especially as it gains a good Optical Clock and BEC quantum tests.
- We are looking for contributors and partners for this effort.

Auxiliary Information

Potential Intra-Swarm RF Protocol of Interest to VLBI Positional Awareness

- At 3-10 GHz, there is the potential of using 802.15.4-a. There is COTS industrial equipment available that supports:
  - Centimeter level real time range accuracy.
  - Support for up to 11,000 communications nodes.
  - Coherent receivers that support real time ranging.
  - Native Support for store and forward communication.
  - Based on nanosecond pulses with a 3.9 MHz (or higher) pulse repetition rate in 500 Mhz or 1 GHz channels.
- We propose consideration of this protocol as a possible candidate for deep space.
- For a variety of reasons, terrestrial WiFi - 802.11a (C band) or 802.11b (S band) - is not nearly as suitable for use as a deep space standard.

802.15.4a Channel Assignments.

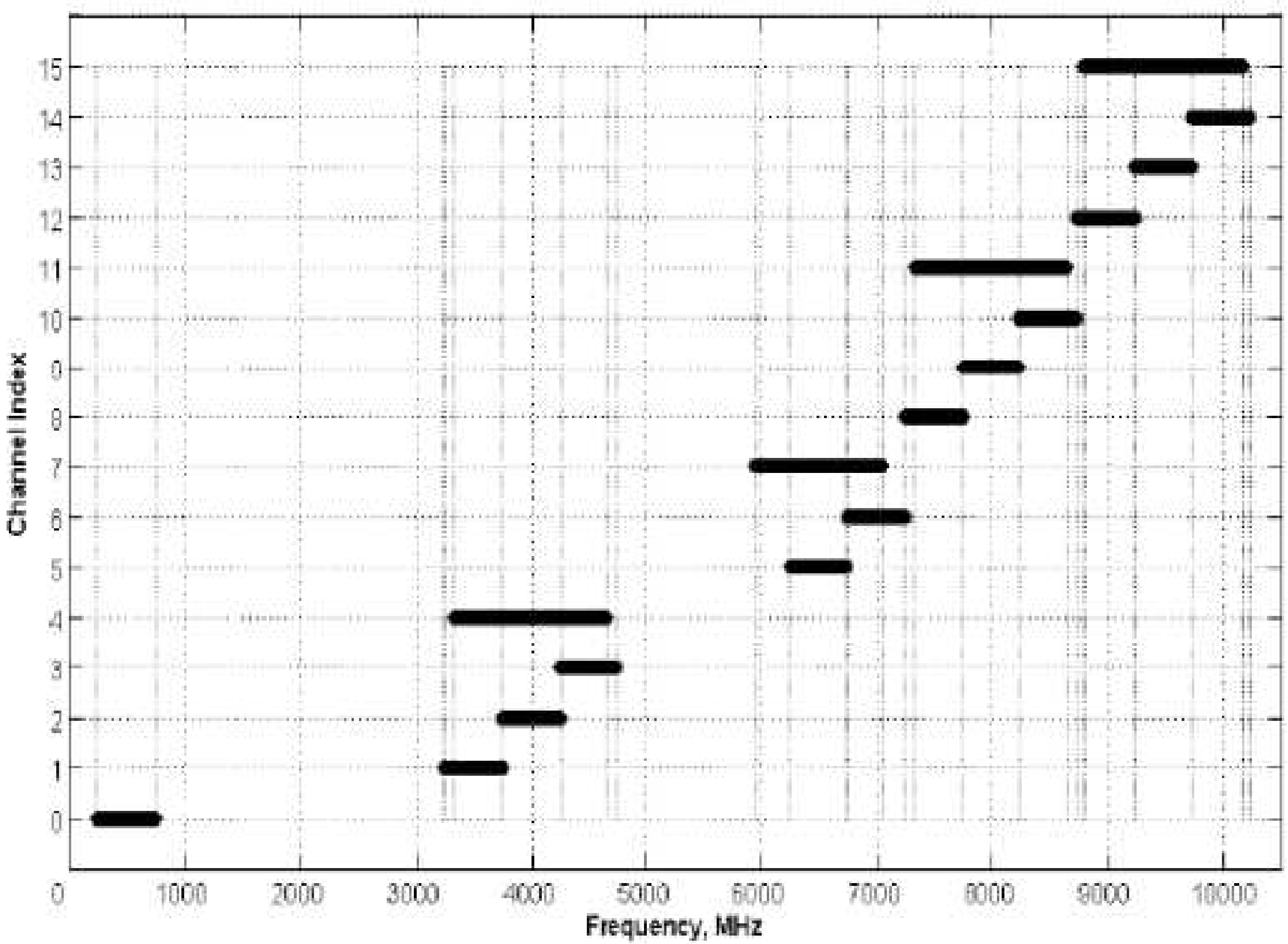
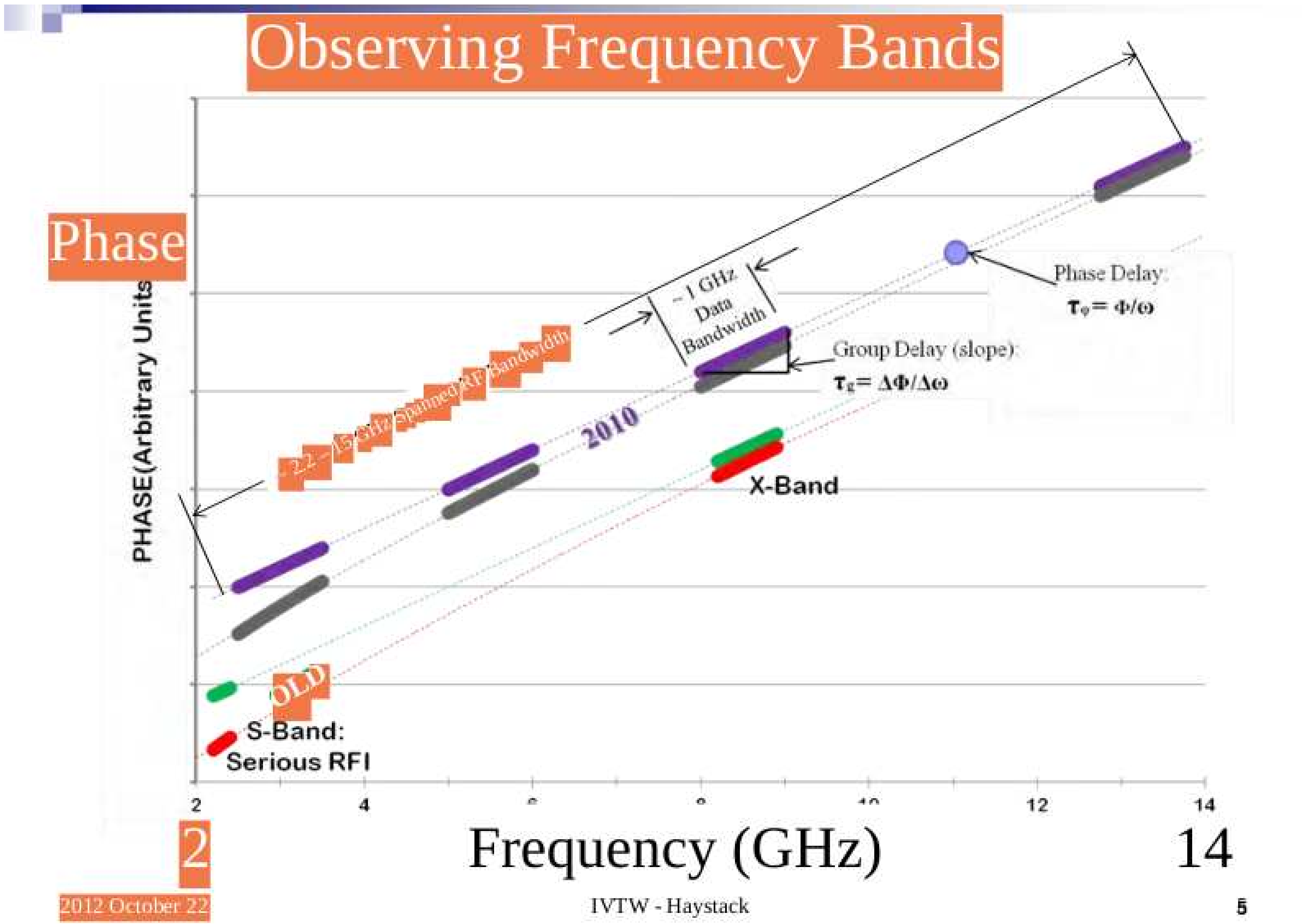


Figure 16-12—HRP UWB PHY band plan

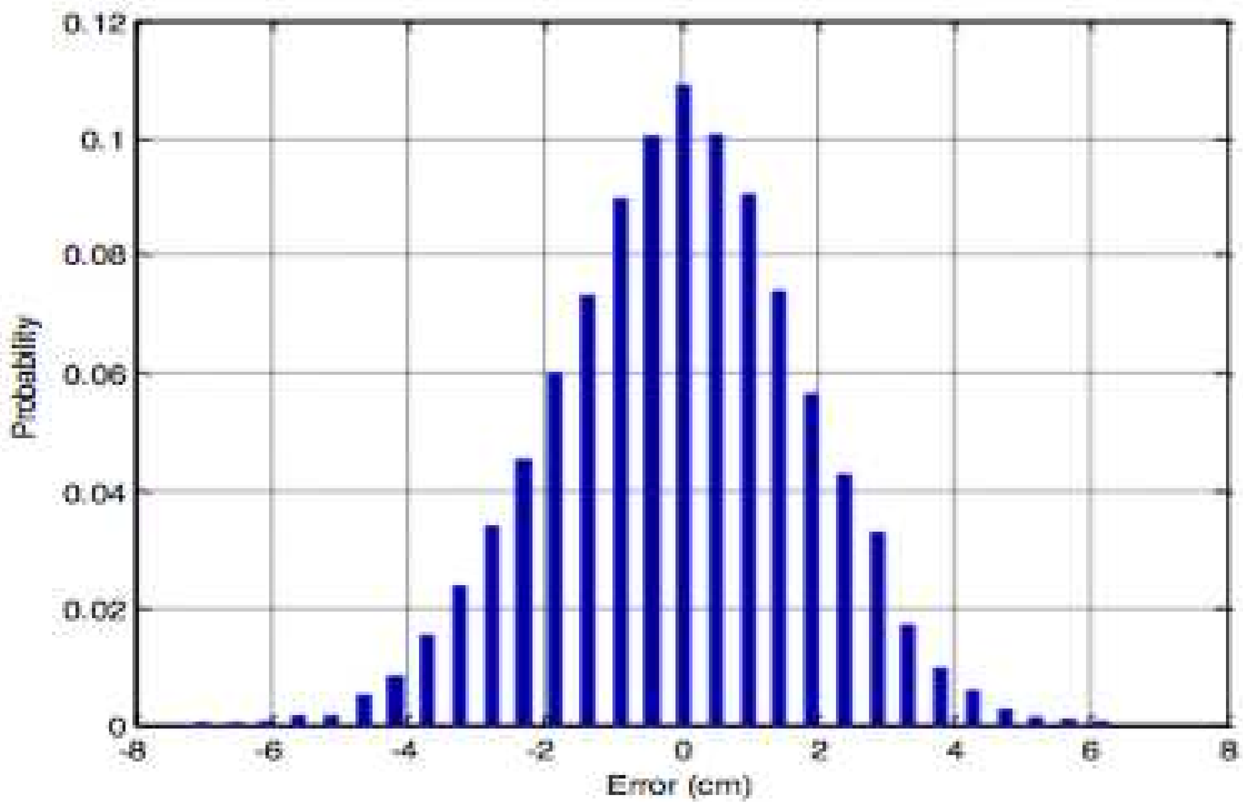
This spread in frequency, and even some of the frequency channels, is very close to the new VGOS frequency choices.

Possible VGOS Channel Assignment.



Source: Arthur Niell Presentation.

Round-trip ranging error from the DEC1000 802.15.4a communications module.

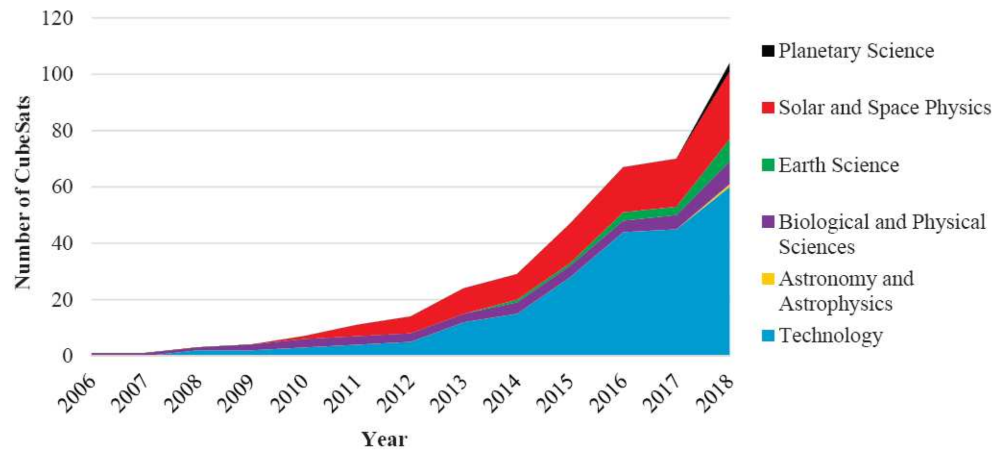


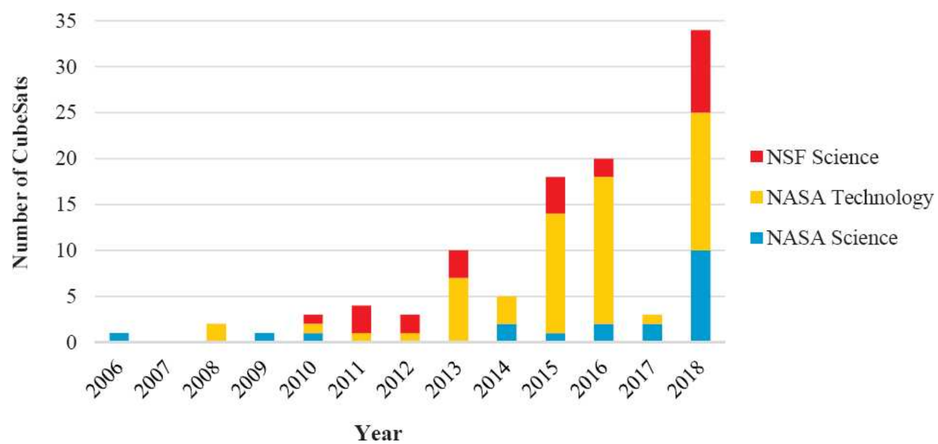
With round trip ranging, accurate time of flight can be obtained without requiring ultra-stable oscillators. This will enable intra-swarm clock synchronization as well.

The Small Spacecraft (SmallSat) Revolution

- A SmallSat can be taken generically to be $\lesssim$ 100 kg.
- CubeSats are based on a 10 x 10 x 10 cm cube ("1 U"), and are roughly 1 kg per U.
- Femtospacecraft are (by my definition) $\lesssim$ 100 gm.
  - Our Pixies are femtospacecraft being developed for deep space functions.
  - A Pixie is 80 x 40 x 9 mm with a mass $<$ 50 grams.
- The smallest Smallsats (so far) are the Chipsats (Credit Card Sized)
  - The Mason Peck / Zac Manchester Sprites - 35 x 35 x 2 mm and a mass of $\sim$5 gm.
- COMPASS (Combined Observational Methods for Positional Awareness in the Solar System) is our proposal to use this technology, plus Ultra-Wide-Band (UWB) Beacons for Positioning, Navigation and Timing (PNT) in Cislunar space and beyond.

Research CubeSats Launched by NASA and the NSF



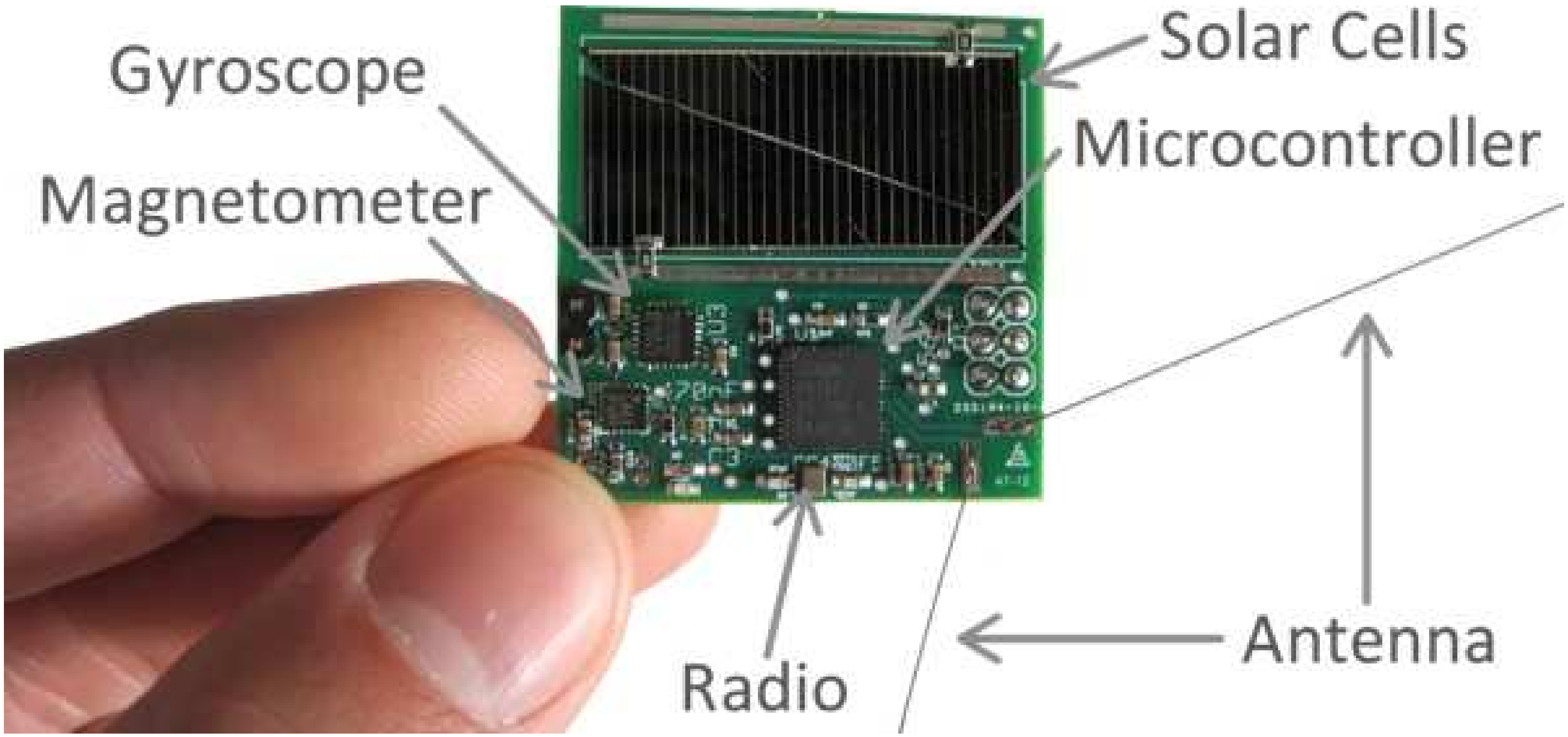


Source - NAS.

The two MARCO 6U Cubesats arrive at Mars.

Artists Impression from NASA/JPL.

A Chipsat.



The Cornell "Sprite" Chipsat. Image is from Manchester et al. [2013].

Principles of Spacecraft Swarm Operation

- To act as a Swarm, a collection of SmallSats must *collectively*
  - Communicate: Determine which swarm members are within reach, and by what means.
  - Collect: Collect and share data from the collected swarm
  - Evaluate: Compare data from each member reachable by the swarm.
  - Distill: Convert the analyzed data into a higher-level summary.
  - Assess: Assess the quality of each data set and the coherence of the whole.
  - Act: Act on the collected data to better fulfill mission objectives.
  - Report: Report the high level reduced data to communications nodes.

References

R. W. King, I. Counselman, C. C., and I. I. Shapiro. Lunar dynamics and selenodesy: Results from analysis of VLBI and laser data. *J. Geophys. Res.*, 81(B35):6251–6256, Dec 1976. doi: 10.1029/JB081i035p06251.

G. Klopotek, T. Hobiger, R. Haas, F. Jaron, L. La Porta, A. Nothnagel, Z. Zhang, S. Han, A. Neidhardt, and C. Plötz. Position determination of the Chang'e 3 lander with geodetic VLBI. *Earth, Planets, and Space*, 71(1):23, Feb 2019. doi: 10.1186/s40623-019-1001-2.

Z. Manchester, M. Peck, and A. Filo. KickSat: A Crowd-Funded Mission To Demonstrate The Worlds Smallest Spacecraft. In *Proceedings of the 27th Annual AIAA/USU Conference on Small Satellites, Standards and Education*, page 111, Aug. 2013. URL `http://digitalcommons.usu.edu/smallsat/2013/all2013/111/`.

S. V. Pogrebenko, L. I. Gurvits, R. M. Campbell, I. M. Avruch, J.-P. Lebreton, and C. G. M. van't Klooster. VLBI tracking of the Huygens probe in the atmosphere of Titan. In A. Wilson, editor, *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, volume 544 of *ESA Special Publication*, pages 197–204, Feb. 2004.